Atelier “Physique théorique des 2 infinis”
07-08 juin 2021

Heavy quark production in pp and AA collisions

The St Graal Quest

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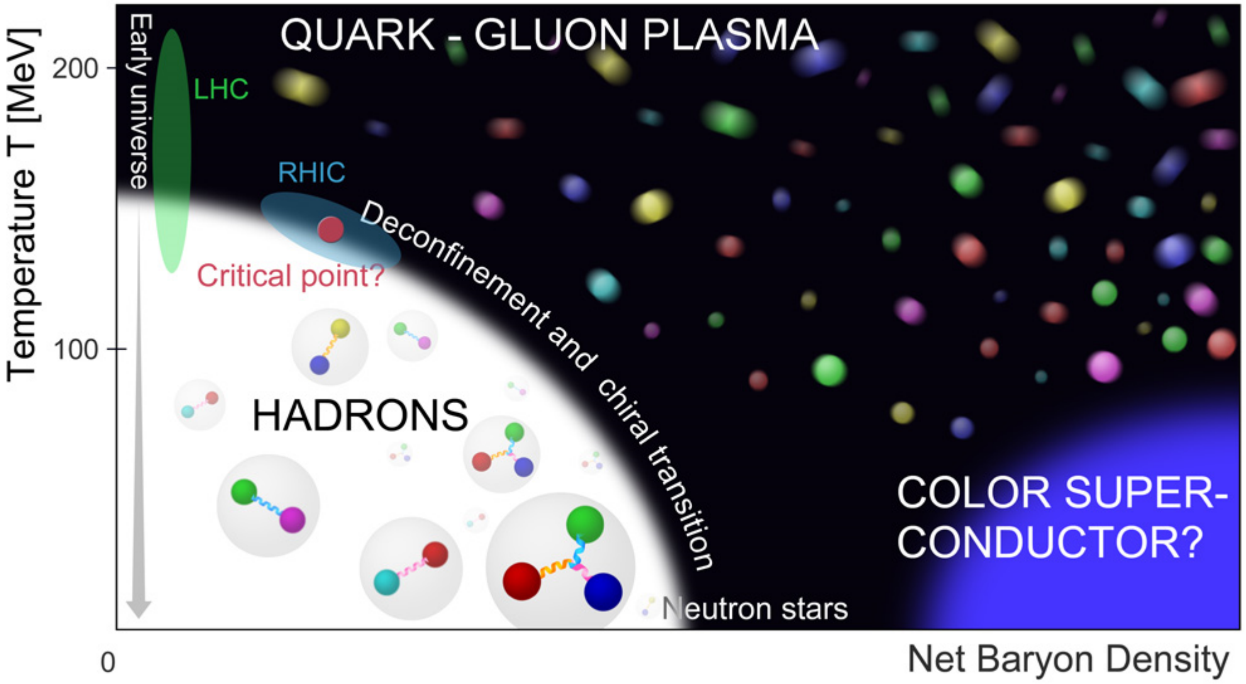
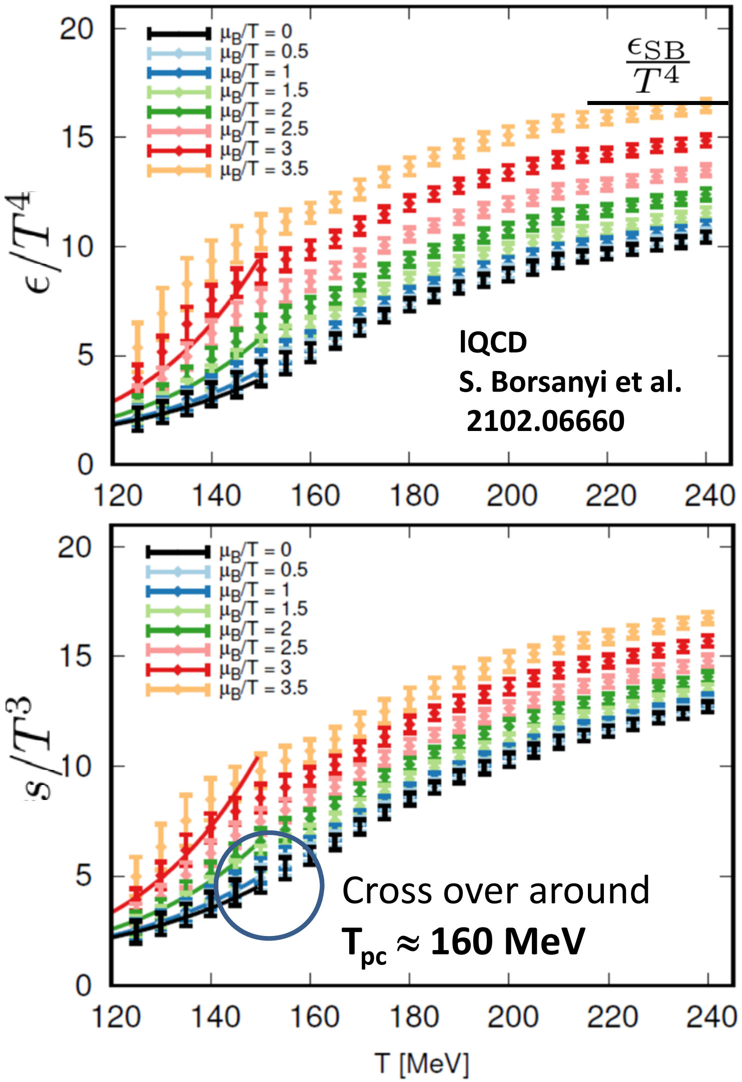
Adopted viewpoint: broad overview. For more specialized viewpoint: recent plenary talk of Min He at « Strangeness in Quark Matter » or « Heavy-Flavor Transport in QCD Matter » at ECT* (https://indico.ectstar.eu/event/98/overview)

Qui : J. Aichelin (Nantes), PB Gossiaux (Nantes), Th Gousset (Nantes), M Nahrgang (Nantes), K. Werner (Nantes) : **IN2P3 theory project EPOS-HQ**
Collaborateurs potentiels en France : JP Blaizot (CEA Saclay), I. Schienbein (Grenoble), J-Ph Guillet (Annecy)
Réseau international de théoriciens : S. Bass, E. Bratkovskaya, R. Rapp, A. Rothkopf, Xin-Nian Wang,.. STRONG 2020 (**Networking activity HF-QGP**)
Collaborations expérimentales impliquées : les 4 collaborations exp. au LHC + RHIC

QCD Phase diagram



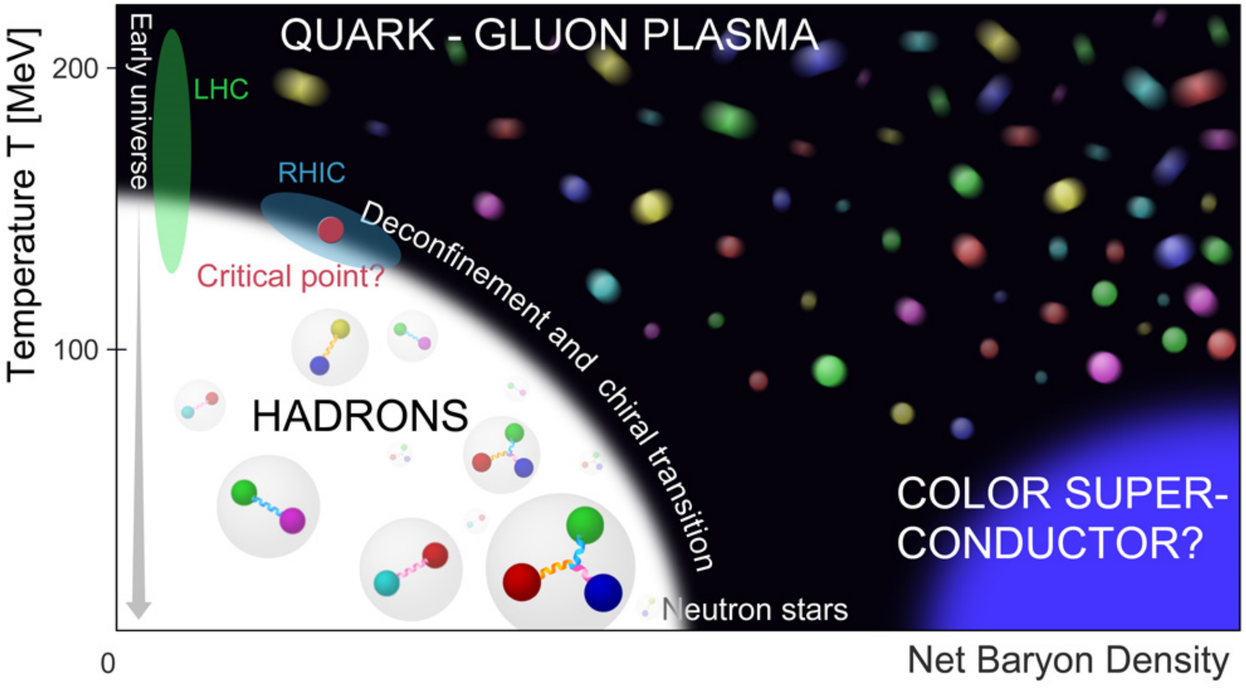


lQCD
S. Borsanyi et al.
2102.06660

Cross over around
$T_{pc} \approx 160$ MeV

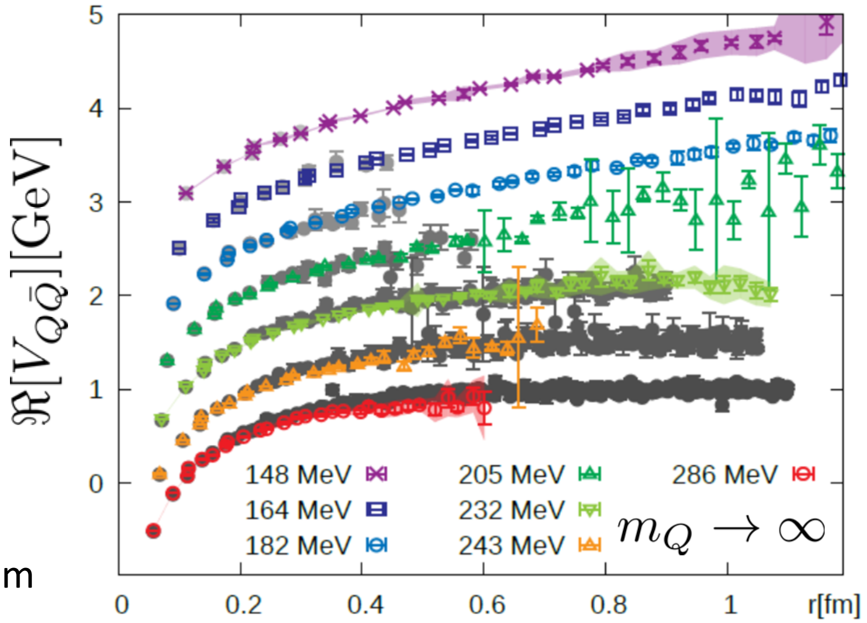
- Around **$T_{pc} \approx 160$ MeV** :
  - o Strong modification of the Polyakov Loop (order parameter for deconfinment)
  - o *gradual* increase of the effective degrees of freedom
- **Challenge : understand the properties of charm quark in this QGP medium** (in this talk: mainly at μ_B=0).

QCD Phase diagram



$$V(r) = \lim_{t\to\infty} \frac{i\partial_t W(t,r)}{W(t,r)}$$

Burnier et al. Phys. Rev. Lett. 114, 082001 (2015)



Grey symbols : free energy

- Challenge : understand the properties of charm quark in this medium (in this talk: mainly at μ_B=0).
- A first answer <- the analysis of the static $Q - \bar{Q}$ potential on the lattice.
- Gradual disappearance of the « long range » force, while the r<0.3 fm « Coulomb-like » core survives at higher temperature.

Physical Picture at large Temperature : HTL

- Hard thermal loops approximation
- Simple expression of the gluon propagator based on the HTL self energy when external momentum $|k| \approx m_{\mathrm{Deb}} \approx g(T)\,T << p \approx T$ ⇔ weak coupling $g(T) << 1$ and perturbative schemes
- If energy transfer is small (ok is at least one of the quark is heavy ./. m_{Deb}) => Interaction reduces to a simple Debye-screened potential

$$V_{\mathrm{HTL}}(r,t) \approx -\frac{\alpha}{r}\, e^{-m_D r}$$

- Light partons acquire thermal mass α gT as well as collisional width (spectral function)

Masses:

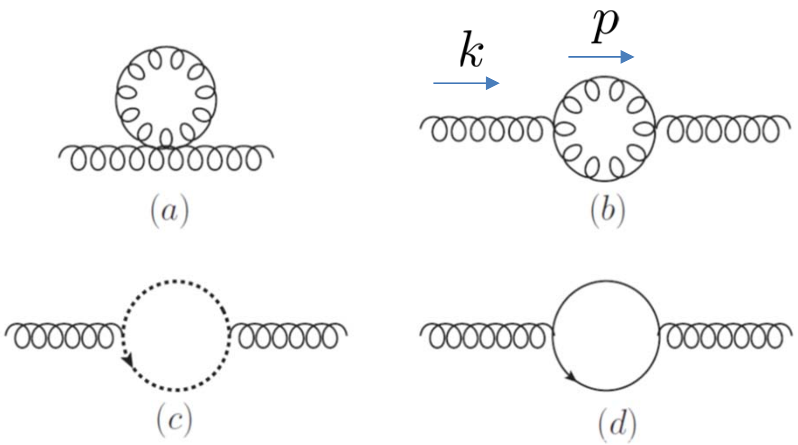
$$M^2_{q(\bar{q})}(T,\mu_B) = \frac{N_c^2-1}{8N_c} g^2(T,\mu_B)\left(T^2+\frac{\mu_q^2}{\pi^2}\right)$$

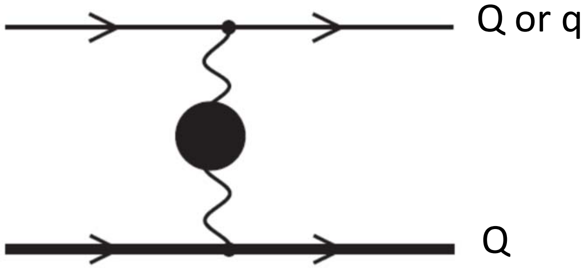
$$M_g^2(T,\mu_B) = \frac{g^2(T,\mu_B)}{6}\left(\left(N_c+\frac{1}{2}N_f\right)T^2+\frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

Widths:

$$\gamma_{q(\bar{q})}(T,\mu_B) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2(T,\mu_B)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_B)}+1\right)$$

$$\gamma_g(T,\mu_B) = \frac{1}{3}N_c\frac{g^2(T,\mu_B)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_B)}+1\right)$$



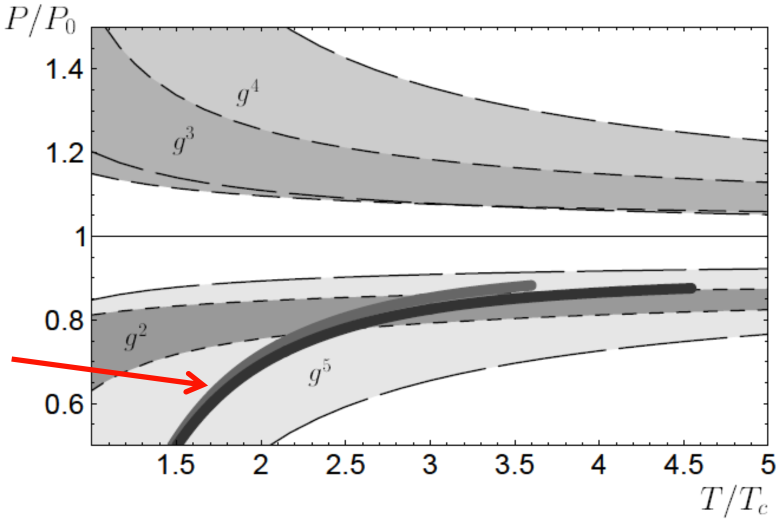


Some nice reviews : **Iancu & Blaizot (2000), Ghiglieri et al. (2020),…**

Physical Picture at large Temperature : HTL

- However, lessons from the past (EOS) : naive HTL approach does not converge uniformly;
- Need clever ressumation and interpretation, as well as extra prescription for fixing m_D (HTL perturbation theory)
- => what about remnants of the confining force ?
- Answer about the applicability might also depend on the considered quantity
- Usually better suited for short range description $r \lesssim m_D^{-1}$

For values of the T achievable nowadays on earth, adding more and more terms simply leads to larger theoretical error bands !!!



lQCD

Kraemmer & Rebhan (2004)

Figure 6. Strictly perturbative results for the thermal pressure of pure glue QCD as a function of T/T_c (assuming $T_c/\Lambda_{\overline{\mathrm{MS}}} = 1.14$). The various gray bands bounded by differently dashed lines show the perturbative results to order g^2, g^3, g^4, and g^5, using a 2-loop running coupling with $\overline{\mathrm{MS}}$ renormalization point $\bar{\mu}$ varied between πT and $4\pi T$. The thick dark-grey line shows the continuum-extrapolated lattice results from reference [154]; the lighter one behind that of a lattice calculation using an RG-improved action [155].

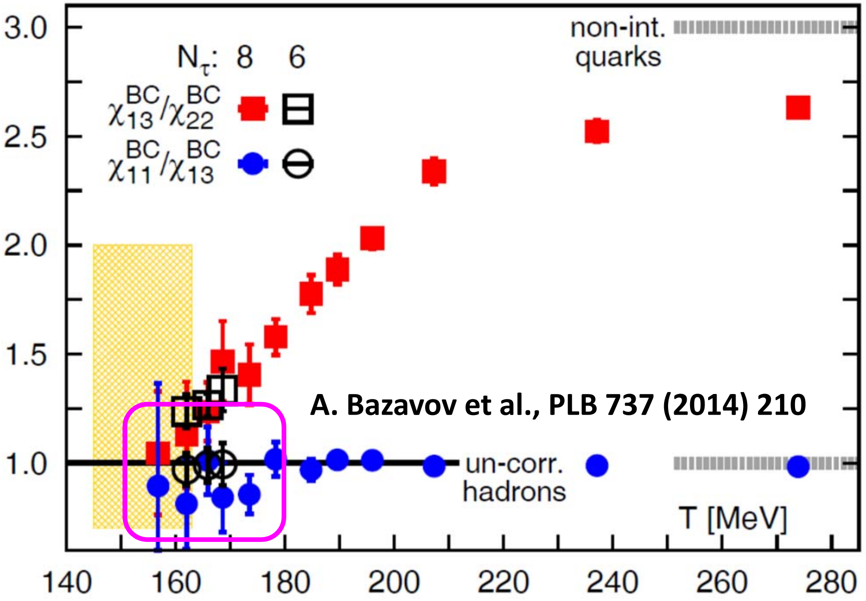
Need for further ressummations **(early 2000's, fi: Blaizot, Iancu & Rebhan)**

Physical Picture around T_{pc}

- Several indications that charm is not weakly interacting around T_{pc} (screening masses, correlators,…)
- Quark susceptibilities on the lattice :

$$\chi^{BC}_{mn} = \left.\frac{\partial^{m+n} p(T,\mu_B,\mu_C)}{\partial \hat{\mu}_B^m \partial \hat{\mu}_C^n}\right|_{\mu_B=\mu_C=0}$$

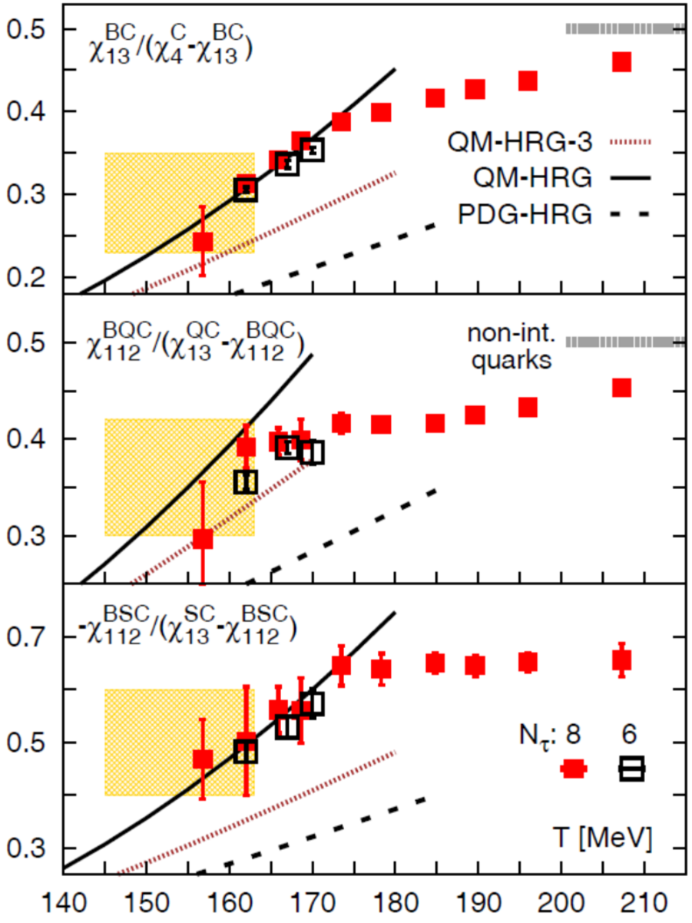
where $\hat{\mu} = \mu/T$



A. Bazavov et al., PLB 737 (2014) 210

All susceptibilities nearly equal, as μ_B and μ_C appear jointly in the charmed-baryonic pressure

Charm baryon to meson pressure



Hadronic nature of charm is confirmed, provided one considers extra charmed-baryonic states from quark models

Physical Picture around T_{pc}

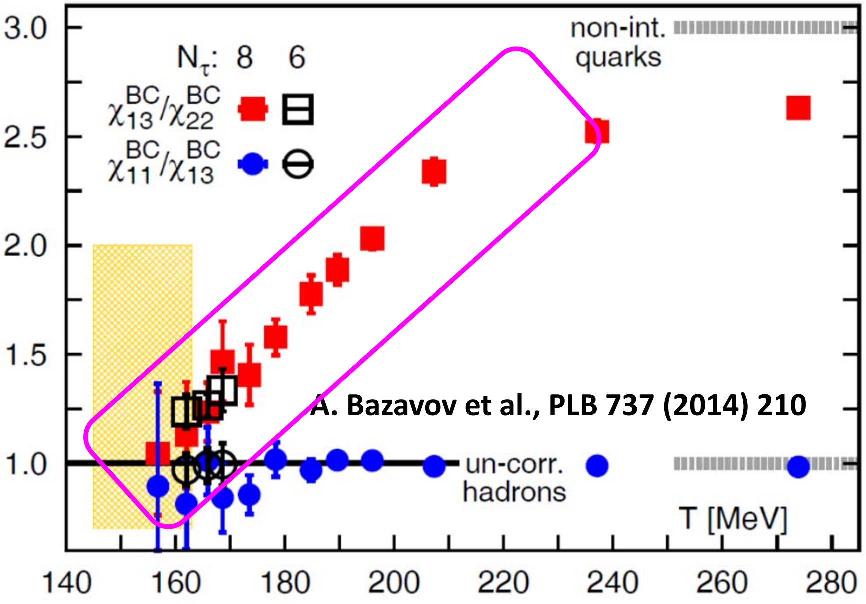
- Several indications that charm is not weakly interacting around Tc (screening masses, correlators,…)
- Quark susceptibilities on the lattice :

$$\chi_{mn}^{BC} = \frac{\partial^{m+n} p(T,\mu_B,\mu_C)}{\partial \hat{\mu}_B^m \partial \hat{\mu}_C^n}\bigg|_{\mu_B=\mu_C=0}$$

where $\hat{\mu} = \mu/T$

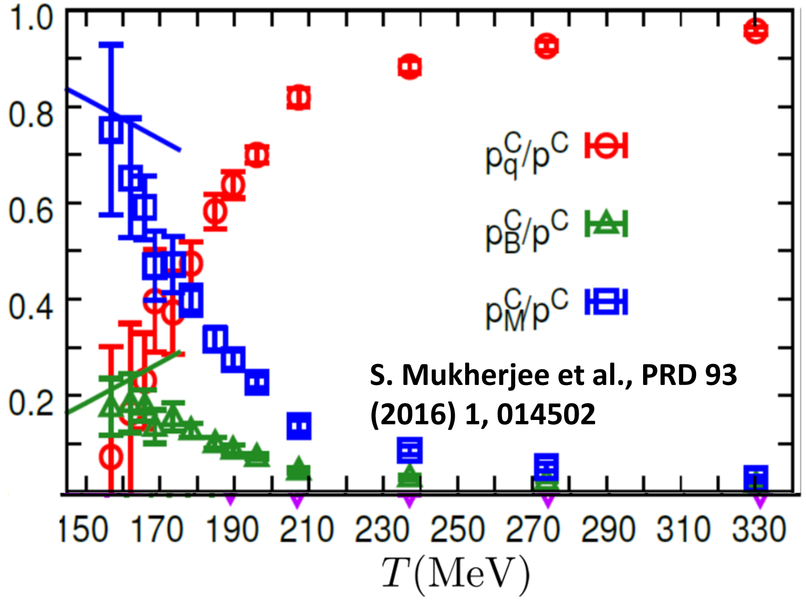
Minimalistic model : $$P^C = P_q^C(T)\cosh(\hat{\mu}_C + \frac{\hat{\mu}_B}{3}) + P_M^C(T)\cosh(\hat{\mu}_C) + P_B^C(T)\cosh(\hat{\mu}_C + \hat{\mu}_B) + \underbrace{\cdots}_{C>1\ \text{(small)}}$$

fractional contributions of partial pressures (PP)



A. Bazavov et al., PLB 737 (2014) 210

Gradual transition from hadronic-like -> non interacting quark values



S. Mukherjee et al., PRD 93 (2016) 1, 014502

PP drop: hadronic resonances become broad at high T and do not contribute

Jakovác, PRD88 (2013), 065012, Biró, Jakovác, PRD(2014)065012

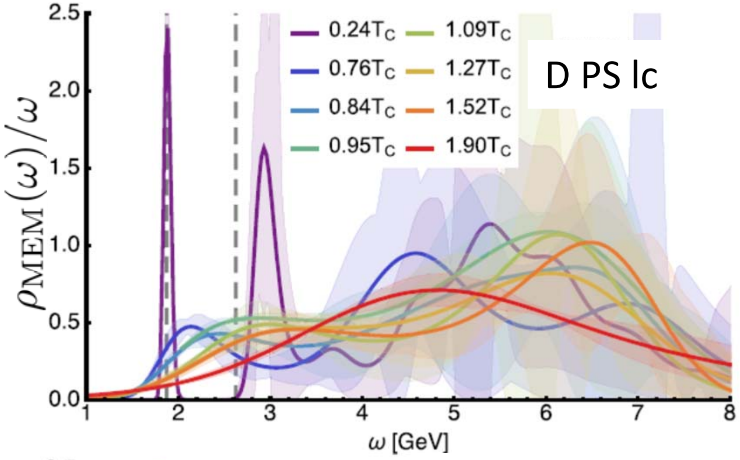
Confirms the resonance picture of Ravagli and Rapp

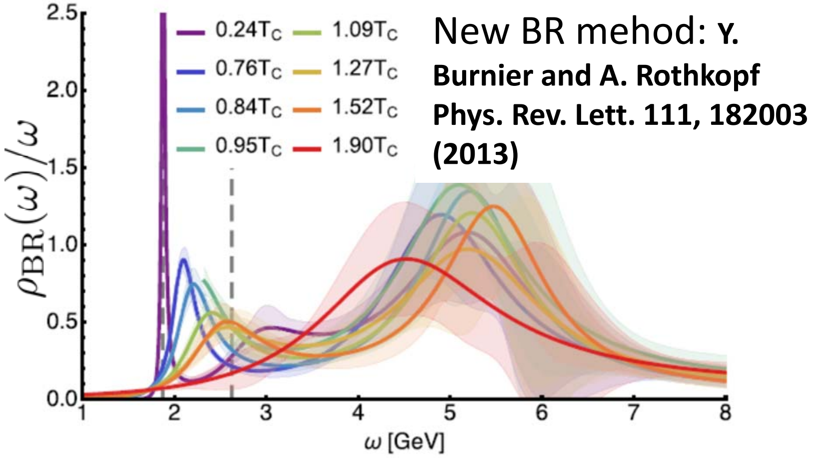
L. Ravagli and R. Rapp, Phys. Lett. B 655 (2007)

Physical Picture around T_{pc}

- Euclidean correlator $G(\tau,T)=\int\rho(\omega,T)K(\tau,\omega,T)d\omega$ with $K(\tau,\omega,T)=\frac{\cosh[\omega(\tau-1/2T)]}{\sinh(\omega/2T)}$

A. Kelly et al, Phys. Rev. D 97(2018), 114509 (2018)



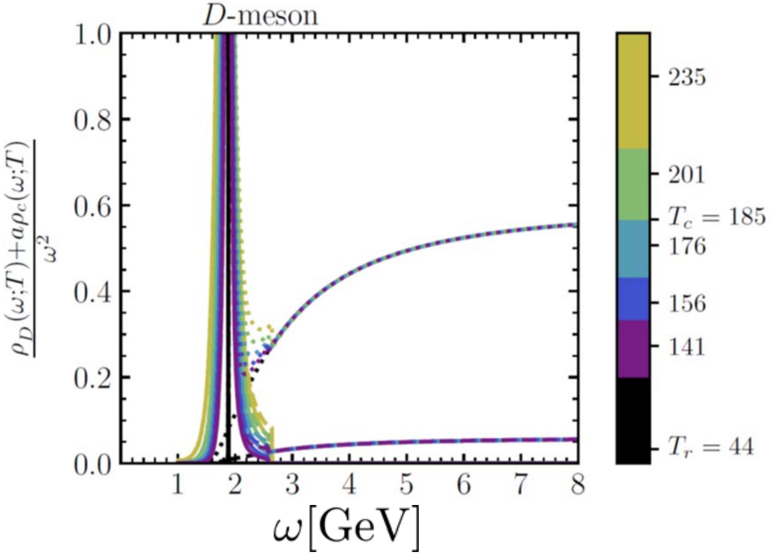


New BR mehod: **Y. Burnier and A. Rothkopf Phys. Rev. Lett. 111, 182003 (2013)**

- Quite challenging inversion problem
- below T_{pc}, the D mesons exhibit consistently more pronounced structures, compared to their D* cousins.
- The BR (inversion) method exhibits remnant peak structures up to T≈ 1.5 T_{pc}
- "The MEM, on the other hand, shows overall more washed out structures, so that at T > T_{pc}, one is hard pressed to identify a genuine peak."

Need further investigation

Glòria Montaña et al, The EPJA56, 294 (2020) … see also talk at SQM 2021



- Effective hadronic theory; spectral function based on GS + continuuum

Physical Picture around T_{pc}

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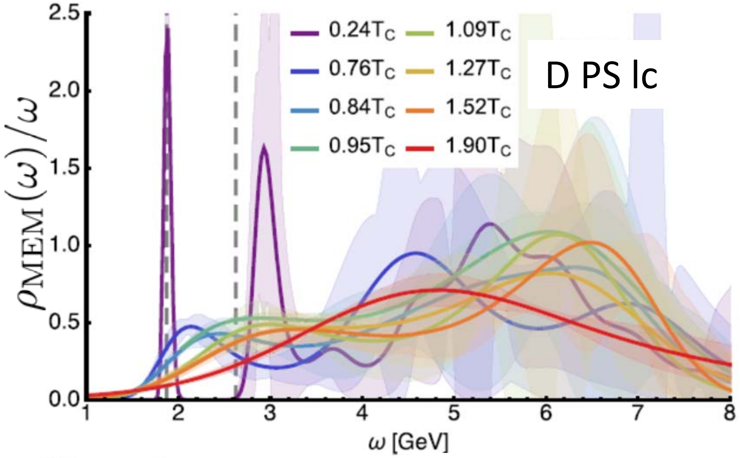

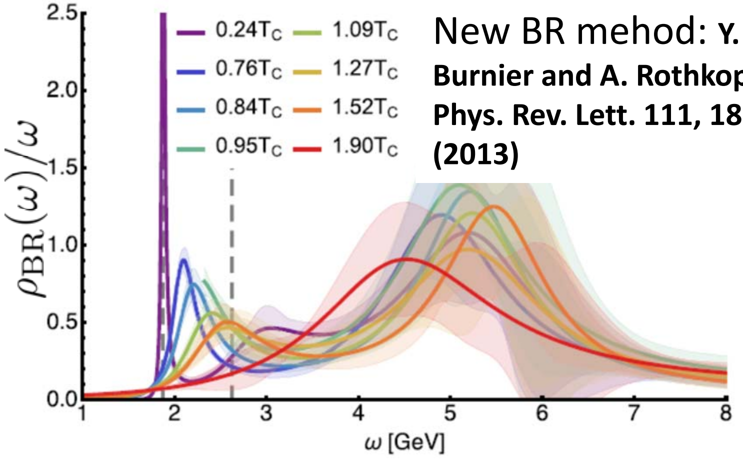

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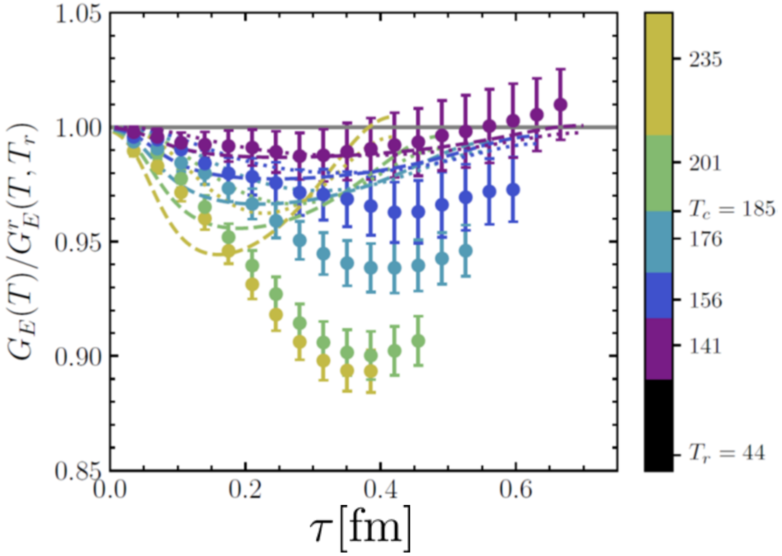
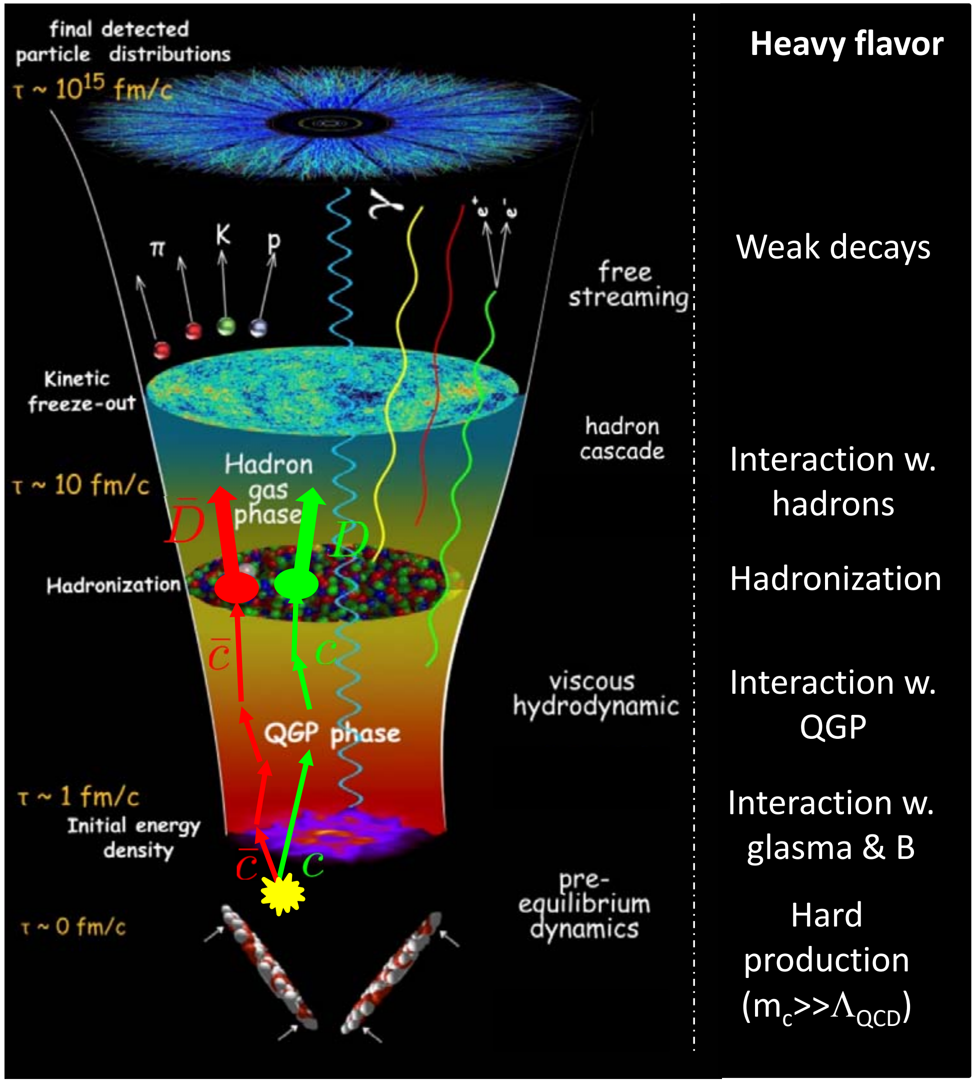


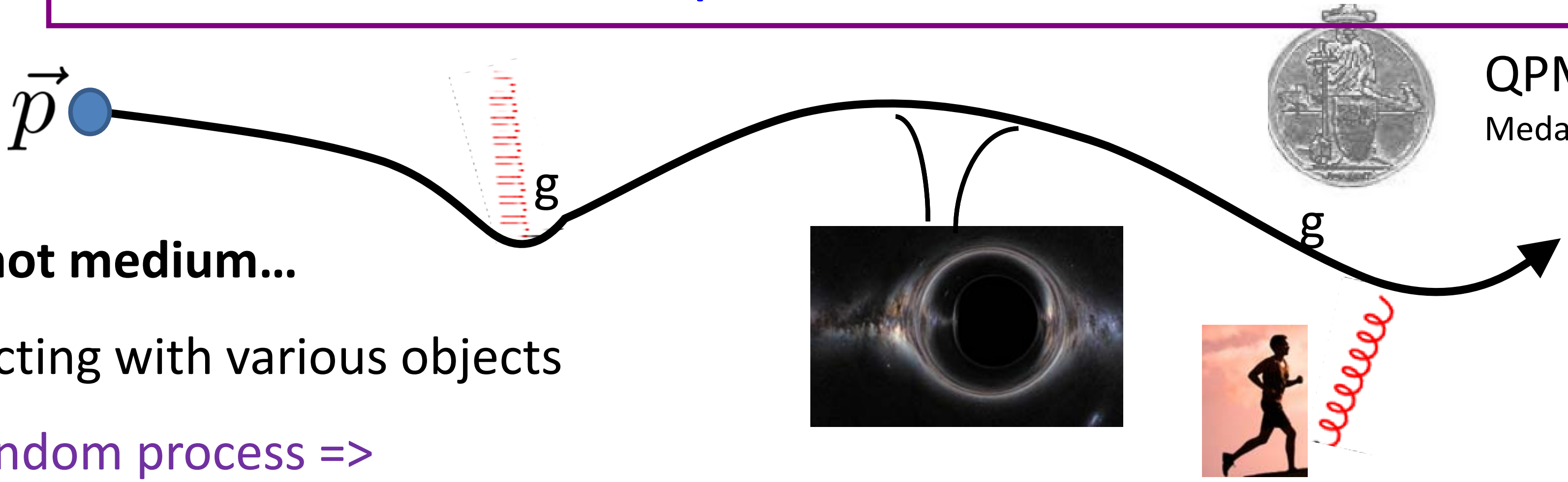
- Effective hadronic theory; spectral function based on GS + continuuum
- Good agreement for low temperature, but large (expected) deviations for T>T_{pc}. (higher states, but also deviation from BW shape).

AA collisions as a playground for testing charm in media



- Produced early ($t \approx 1/m_c$)
  - => No further c-cbar generation in ensuing QGP
  - Initial production well controlled (advantage of $m_Q \gg \Lambda_{QCD}$) : several well established schemes : FONLL (**Cacciari**), GM-VFNS (**Schienbein**)
  - But early phase might not be so innocent (magnetic field, CGC-glasma,…)
- => experience the full deconfined phase + hadronic phase
  - probes « deeper » than most of the other hadronic observables *while not fully thermalized* ($t_{relax} \propto m_Q/T^2$)
  - accumulates several effects => need to compare different systems to better differentiate them
- Produced over a wide range of rapidities and p_T
  - increased richness in scrutinizing the interaction of HQ with medium…
  - but also sets more challenges (interactions for $p_T \ll m_c$, $p_T \approx m_c$, $p_T \gg m_c$, appropriate transport theory ?).
- => Several models have emerged that aim at describing OHF production in AA collisions

Transport coefficients



QPM (Queen’s Police Medail)

HQ in hot medium…

… interacting with various objects

Quasi random process =>

$$-\frac{d}{dt}\langle\vec{p}\rangle = \vec{A}(\vec{p},T) = \eta_D(\vec{p},T)\times\vec{p}$$

$\eta_D[\mathrm{fm}^{-1}]$: Relaxation rate

$$\frac{d}{dt}\langle\vec{p}_{T,i}\vec{p}_{T,j}\rangle = \kappa_T(\vec{p},T)\delta_{i,j}$$

$\kappa_T[\mathrm{GeV}^2\mathrm{fm}^{-1}]$: Transverse diffusion coef. (p space) ; $\boxed{\hat{q} = 2\kappa_T = 4B_0}$

Similar in longitudinal direction

$\kappa_L[\mathrm{GeV}^2\mathrm{fm}^{-1}]$: Longitudinal diffusion coef.

In general, no relation between these coefficients except $\kappa_T = \kappa_L$ for p=0.

Transport coefficients at low momentum $p \approx m_Q$

Langevin regime => Einstein relation: $\kappa = 2TE_Q\eta_D$

$$D_s = \left(= \frac{1}{6}\lim_{t\to\infty}\frac{\langle(\mathbf{x}(t)-\mathbf{x}(0))^2\rangle}{t}\right)$$

For historical reasons, physics displayed as a function of 2πT x the spatial diffusion coefficient

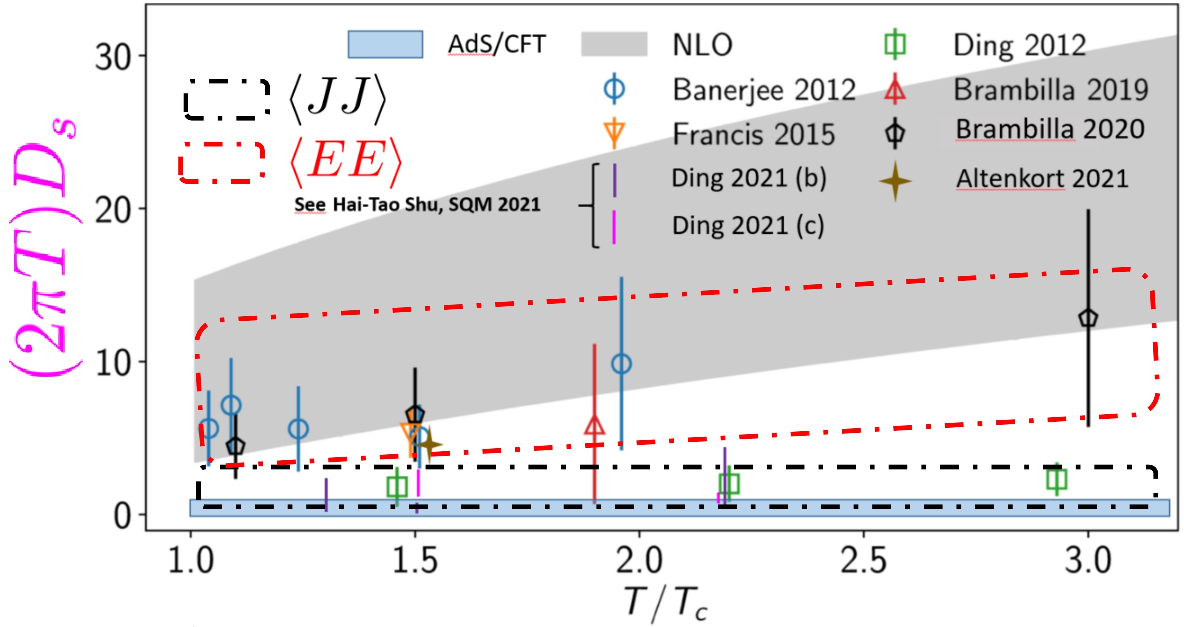
$$\underbrace{(2\pi T)D_s}_{\text{Gauge for the coupling strength}} = \frac{4\pi T^3}{\kappa} = \frac{2\pi T^2}{E_Q\eta_D} \Rightarrow \tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{E_Q}{2\pi T^2}$$

lQCD results

The sole direct rigorous calculation of the transport coeff to my knowledge

$$\tau_{\text{relax}}(T_c) \approx m_Q[\text{GeV}] \times (3 \pm 1.5)\ \text{fm}$$

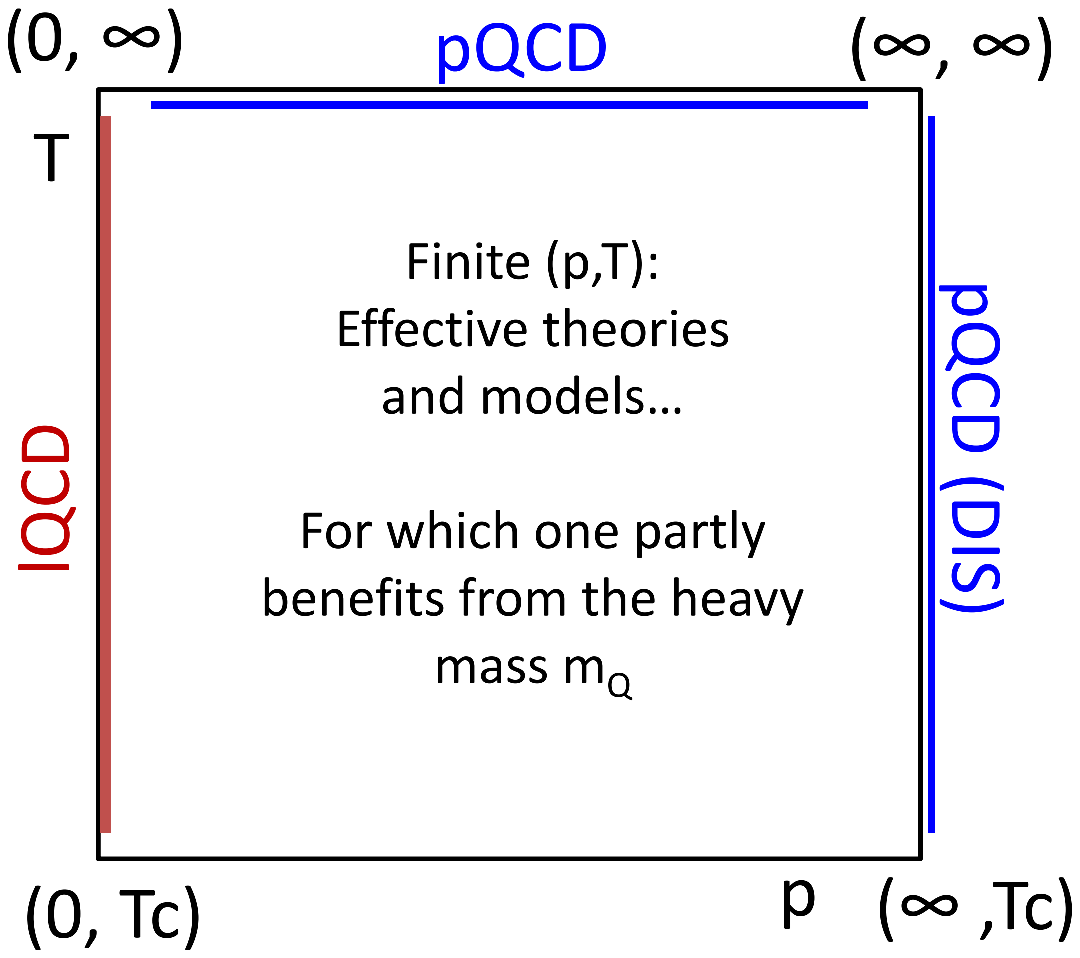
Still not conclusive



2 possible methods : direct current – current correlator (diffusion peak) or field-field benefitting from large m_Q. Tension between the two approaches ?

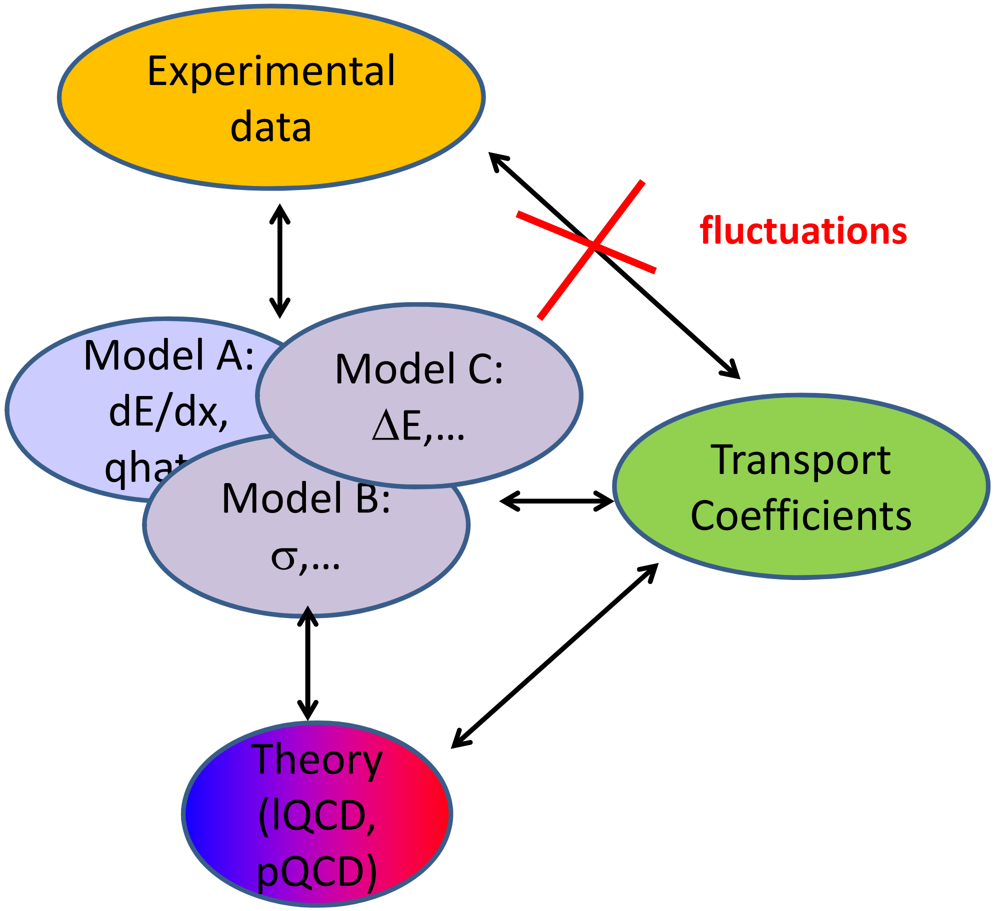
Lanscape of HF theory and modeling in URHIC

Transp. coeff. $\eta_D, \kappa_T, \kappa_L$

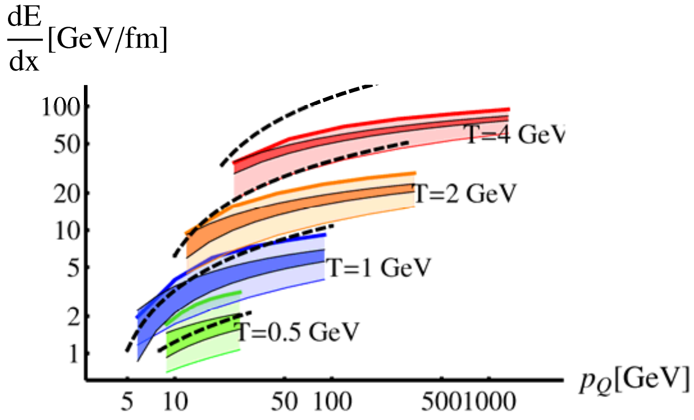


Finite (p,T):
Effective theories
and models…

For which one partly
benefits from the heavy
mass m_Q



pQCD inspired models (f.i. Nantes)

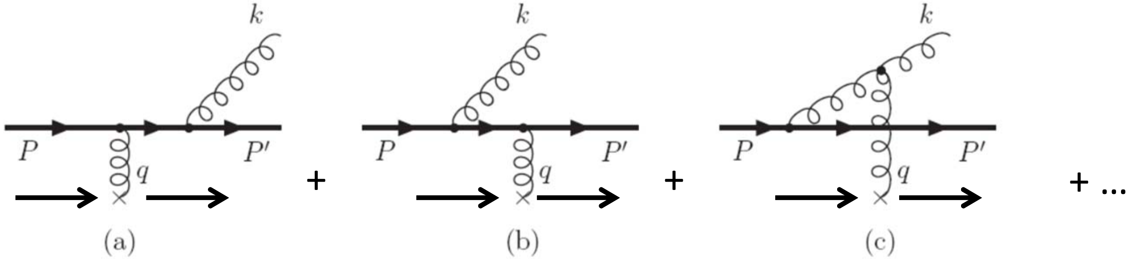


Colisional component

- One-gluon exchange model: reduced IR regulator $\lambda\, m^2_D$ in the hard propagator, fixed on HTL Energy loss at intermediate p_T
- Running coupling α_{eff} (t) and self consistent Debye mass

$$m_{Dself}^2\,(T) = (1+n_f/6)\, 4\pi\alpha_{eff}(m_{Dself}^2)T^2$$

Radiative component



(a) (b) (c)

- Extention of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q) distribution of induced gluon radiation per collision ($\Delta E_{rad}\ \alpha$ E L):

$$P_g(x, \mathbf{k}_\perp, \mathbf{q}_\perp, m_Q) = \frac{3\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2 + x m_Q^2} - \frac{\mathbf{k}_\perp - \mathbf{q}_\perp}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + x m_Q^2}\right)^2$$

- LPM effect for moderate gluon energy

Implemented in MC@HQ + EPOS2(3) through Boltzmann dynamics

But also BAMPS, LBL-CCNU, Duke,…

Quasi particle models (f.i DQPM)

- Non perturbative effects near Tc are captured by α_s(T), leading to thermal masses/widths, determined from fits to lQCD EoS.

A. Peshier et al. PLB 337 (1994), PRD 70 (2004); M. Bluhm et al. EPJC 49 (2007); W. Cassing et al. NPA 795 (2007)

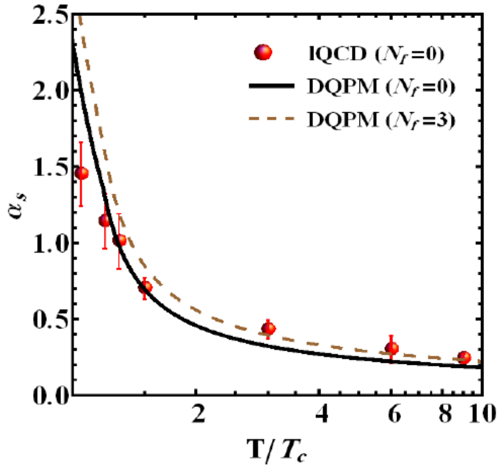
- Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

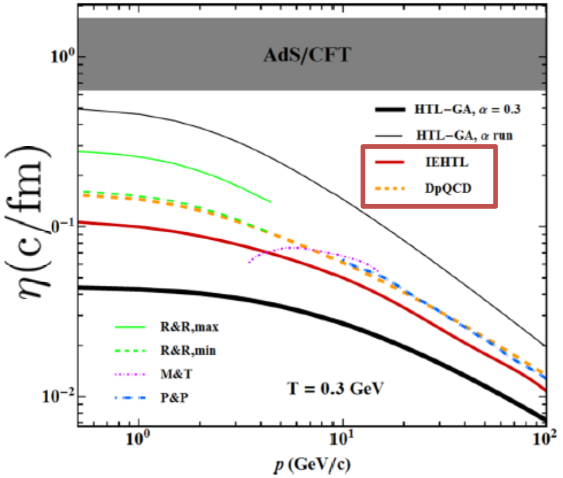
H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

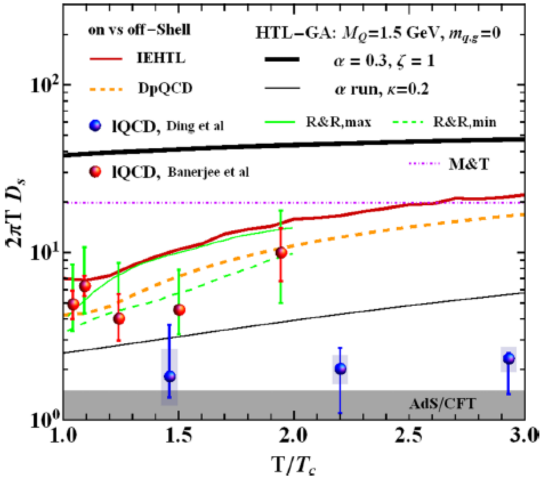
- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilirium transport).

T. Song et al. PRC 92 (2015), PRC 93 (2016)

But also CATANIA







Potential models (TAMU)

- Thermodynamic T-matrix approach, T = V +VGT, given by a two-body driving kernel V, estimated from the lQCD internal/free energy for a static Q-Qbar pair; increase of coupling with QGP at small momentum

D. Cabrera, R. Rapp PRD 76 (2007); H. van Hees, M. Mannarelli, V. Greco, R. Rapp PRL 100 (2008)

- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion (many body theory).

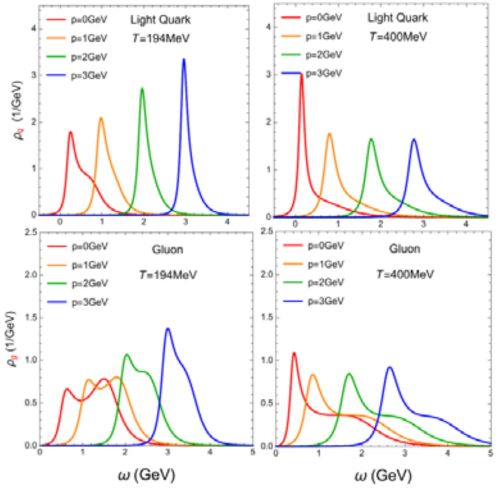
F. Riek, R. Rapp PRC 82 (2010); S. Liu, R. Rapp arxiv:1612.09138

- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions => amplifies HQ-coupling with QGP

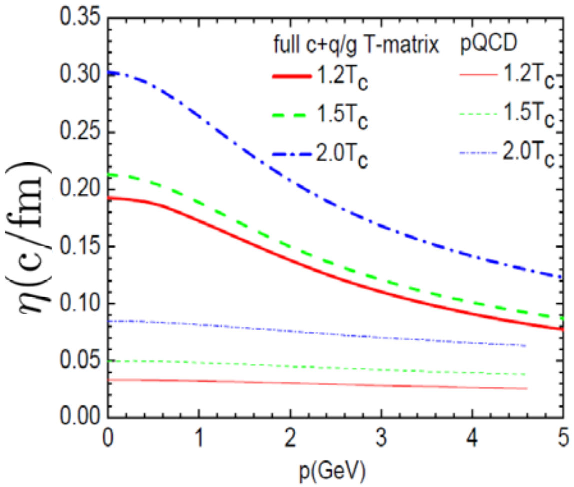
M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)

- Implemented through Langevin dynamics in hydro evolution or in URQMD

- Full quantum treatment of the light quarks (spectral functions)

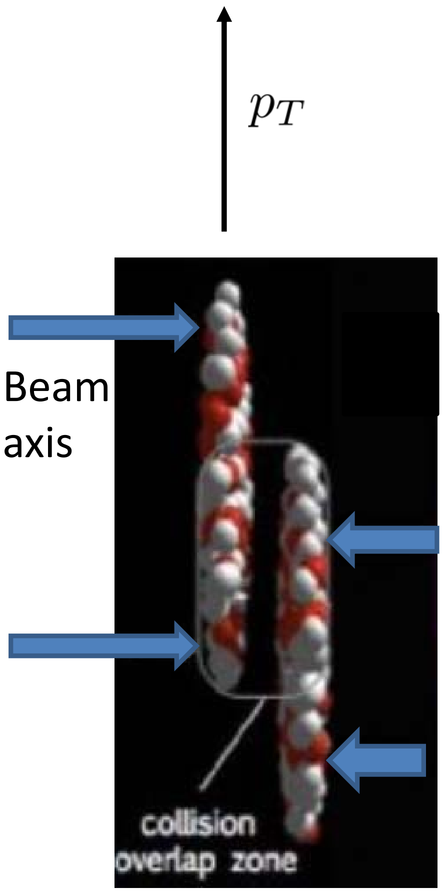


No good q-particle at low p



Large coupling at small p_Q

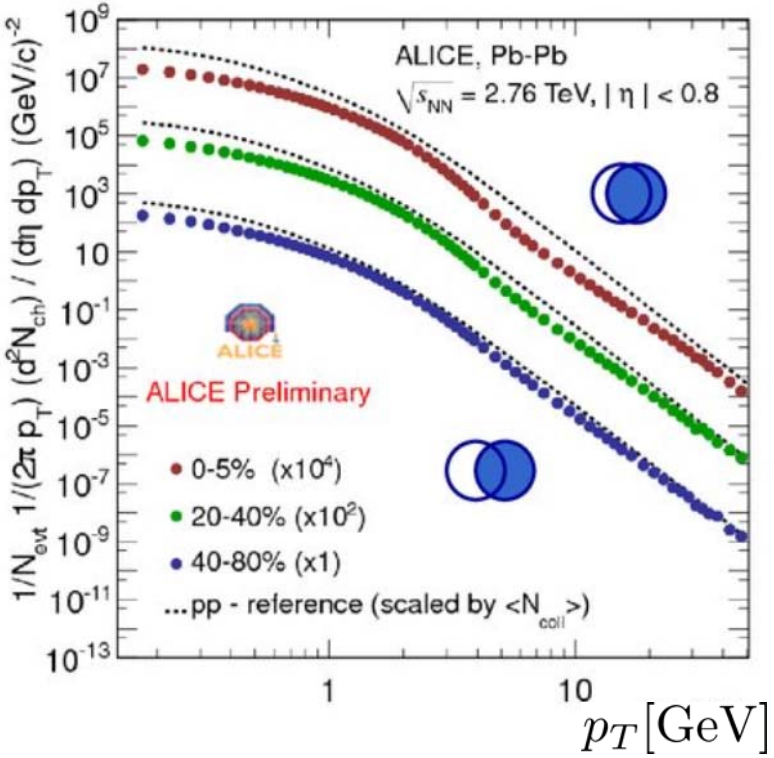
Observable 1: Nuclear modification factor



Beam
axis

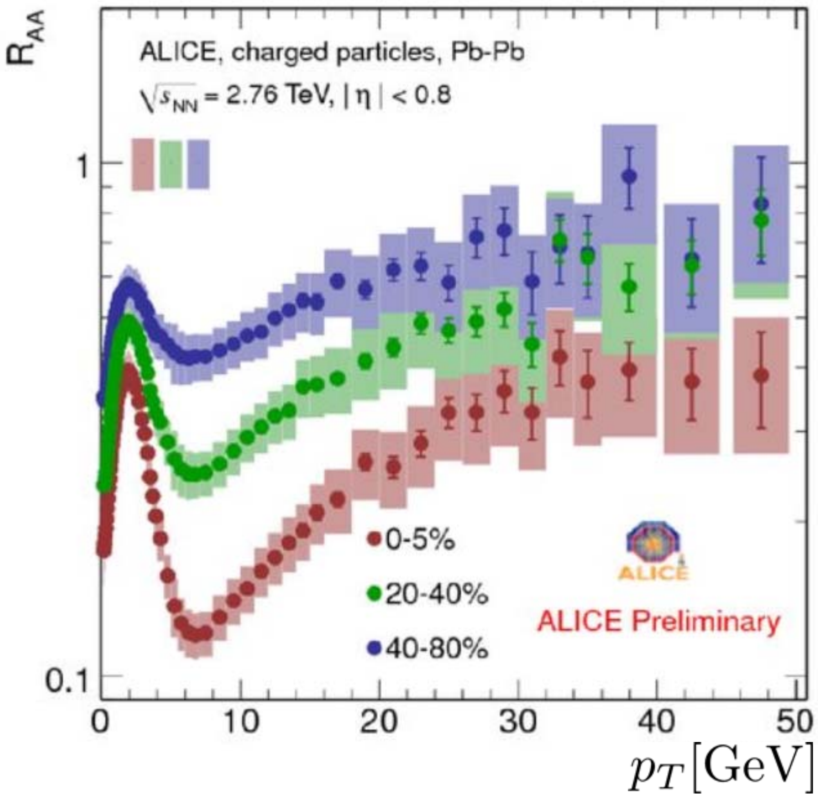
Equivalent number of pp collisions in the overlap: N_{coll}

Charged hadrons p_T spectra



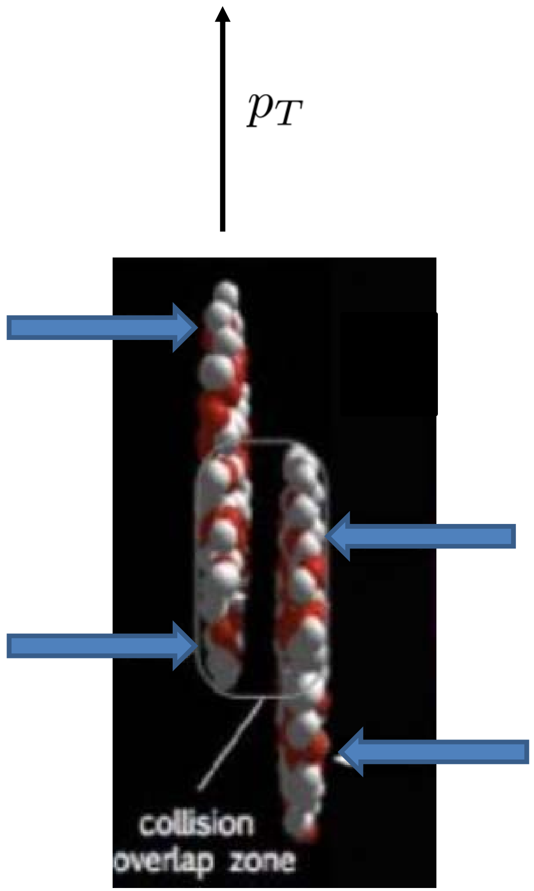
Nuclear modification factor

$$R_{AA}(X) = \frac{\left.\frac{dN^X}{dp_T}\right|_{AA}}{N_{\text{coll}}\left.\frac{dN^X}{dp_T}\right|_{pp}}$$

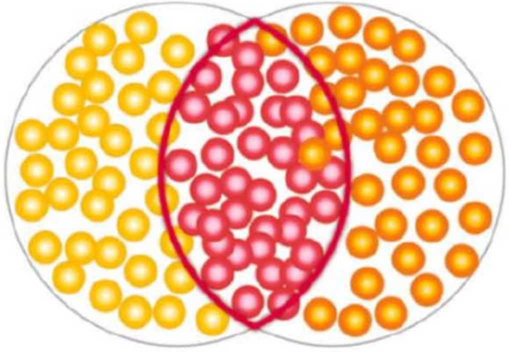


Observable 2: azimuthal flows

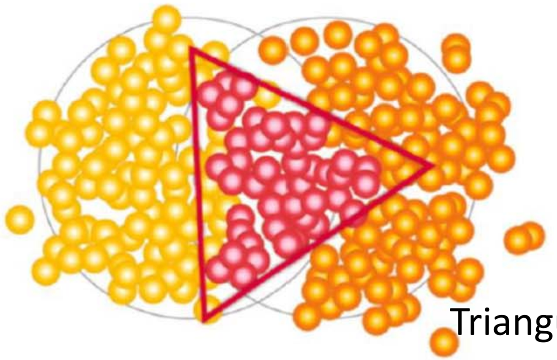
Beam axis (Oz)



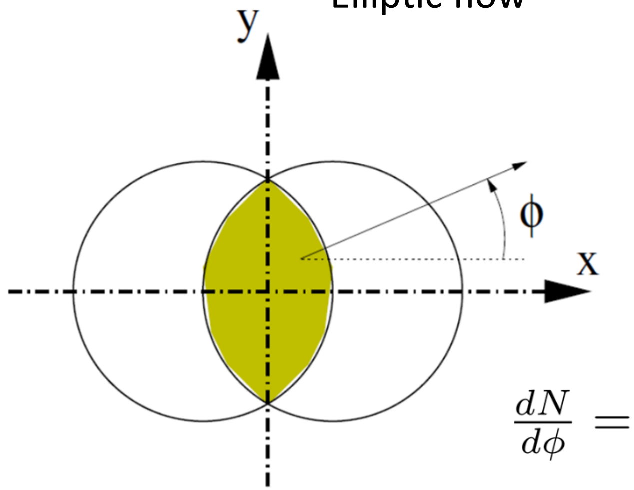
Initial stage of the collisions seen in the transverse plane: Non spherical initial spatial distribution due to eccentricity + fluctuations



Elliptic flow



Triangular flow



… later on converted in anisotropies due to the fluid dynamics evolution.

anisotropies in the final hadrons azimuthal distributions (Fourier series)

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2v_2\cos[2(\phi - \psi_{\mathrm{RP}})] + \cdots\right)$$

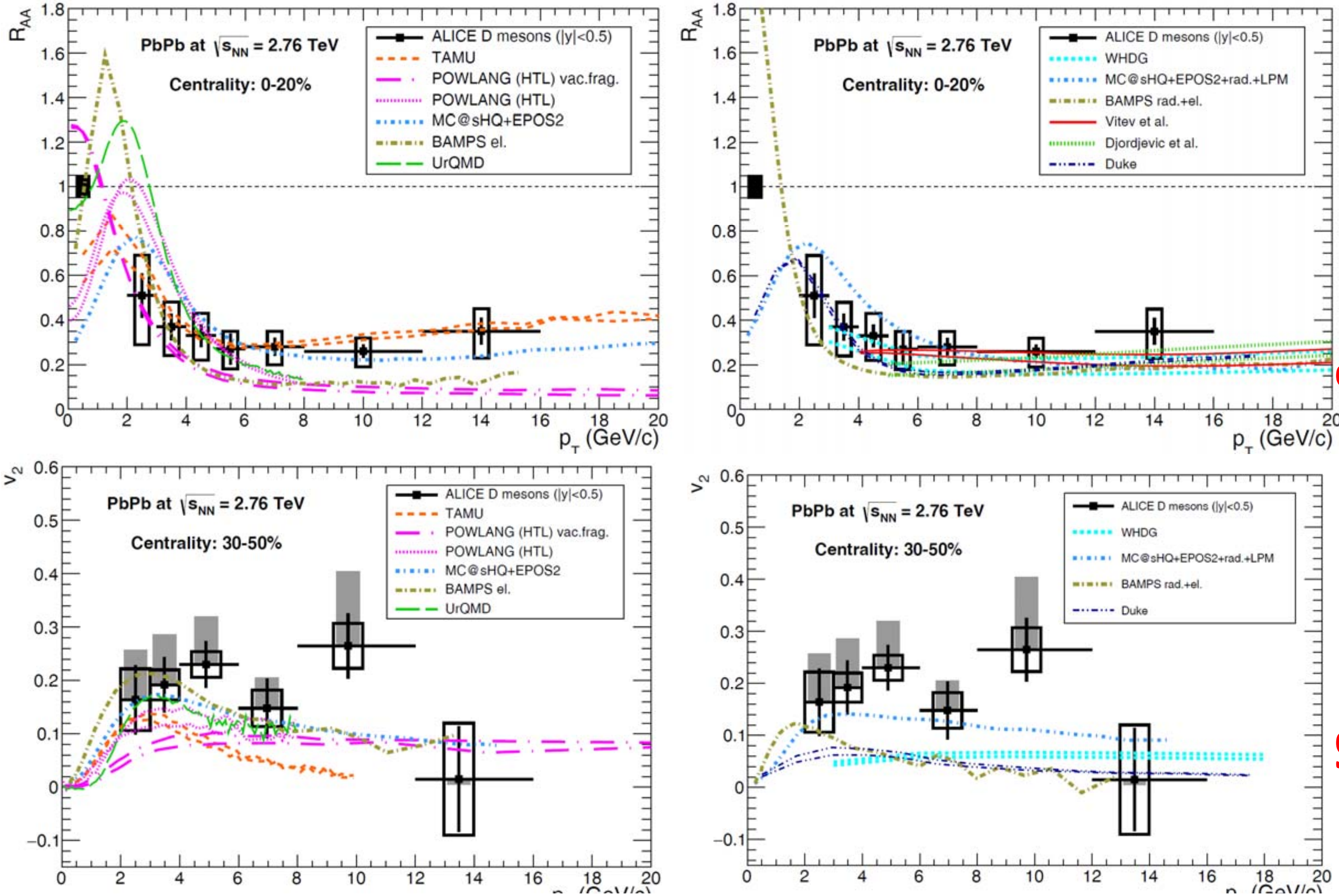
$$v_2 = \langle\cos[2(\phi - \psi_{\mathrm{RP}})]\rangle$$

Models vs DATA at LHC (Sapore Gravis Report compilation)

Eur. Phys. J. C (2016) 76

Purely elastic scatterings

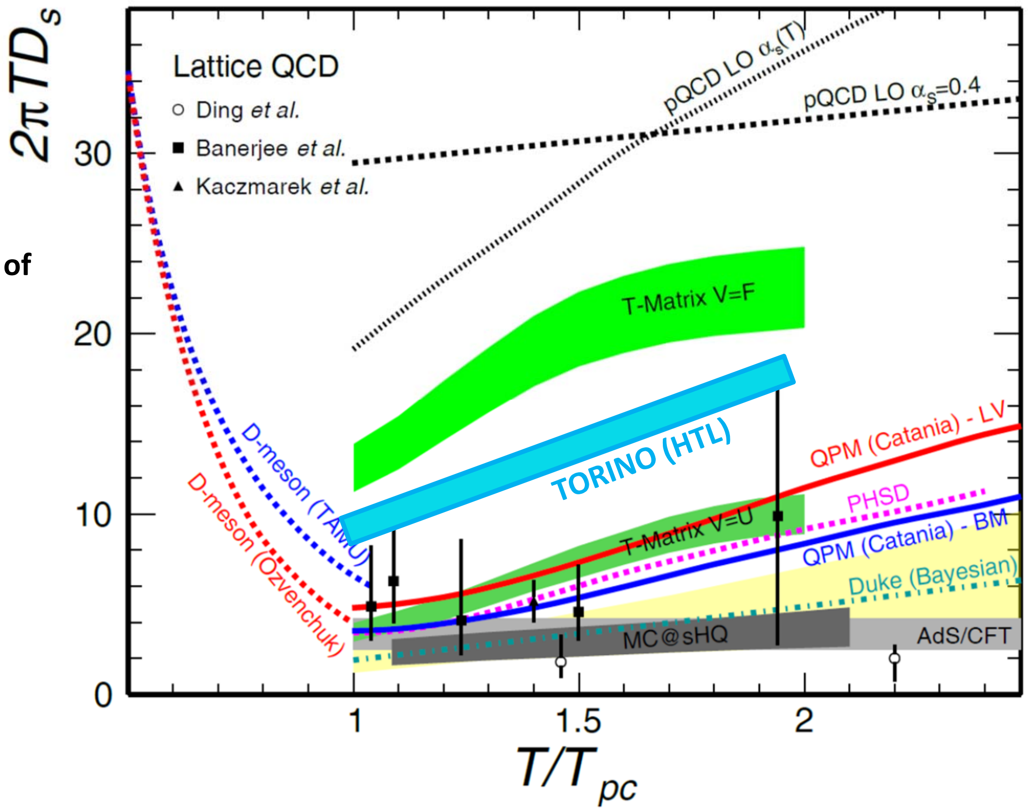
Elastic scatterings + radiative energy loss



Despite various prescriptions for Energy loss, a lot of models can cope with the data

Model summary on $2\pi TD_s$ extraction

X. Dong et al. Annual Review of Nuclear and Particle Science 69:417-445 (2019)



η_D α T^2: pQCD (fixed α_s), AdS/CFT

η_D α T: pQCD (running α_s)

η_D α T^0: QPM, DQPM, U potential (TAMU)

$$(2\pi T)D_s = \frac{2\pi T^2}{E_Q \eta_D}$$

Mild linear increase of $2\pi D_sT$… ⇔ physics beyond pQCD (fixed α_s).

- Most of the values extracted from model comparison with the data are compatible with lQCD calculations !!!
- All together (lQCD, Bayesian analysis and most recent models) make a strong case for physics beyond « weak pQCD LO » around T_c » and at «low» p_T
- However, the question whether one needs to include strong non-perturbative features is still debated … needs to be further addressed in the future.

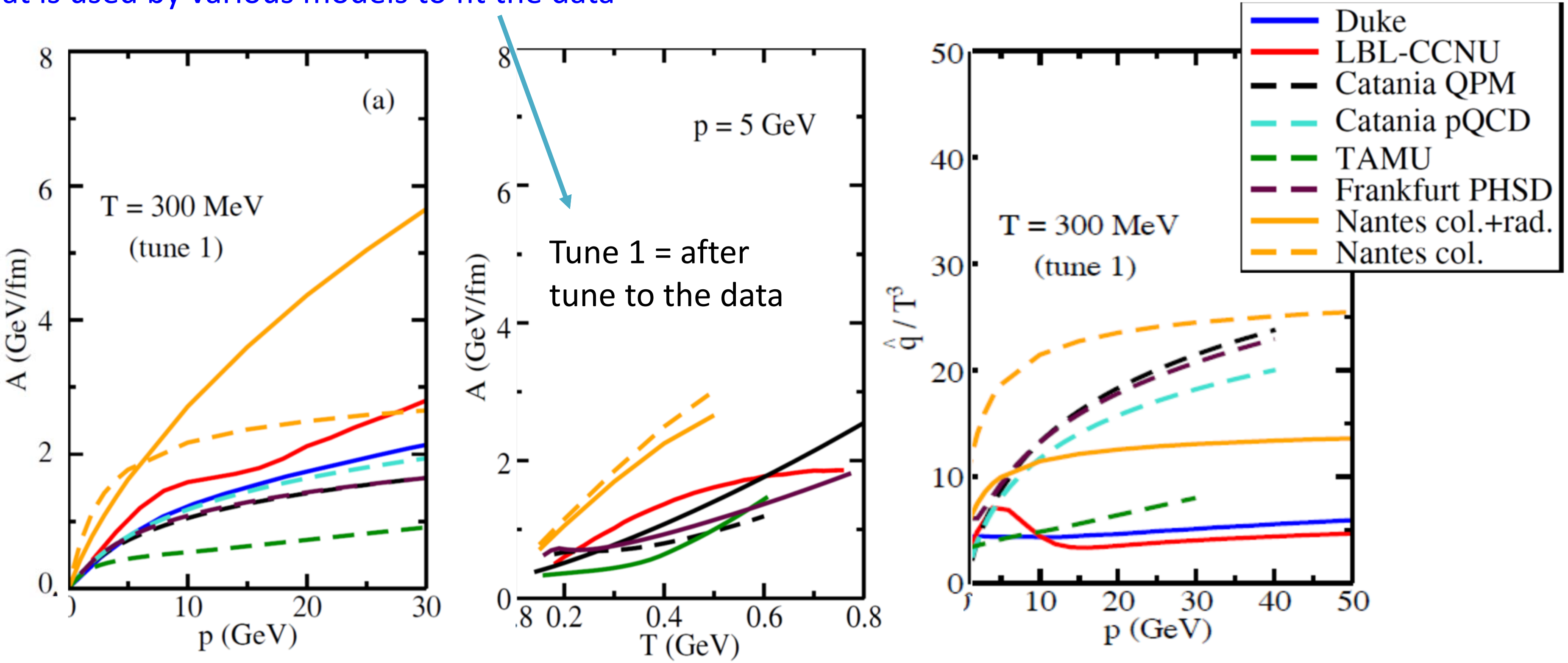
HQ Working Group

S. Cao et al,
Phys.Rev.C 99 (2019)
5, 054907

c-quarks

- Collect and compare the transport coefficients from various models:

  What is used by various models to fit the data



Tune 1 = after tune to the data

- Obviously not satisfying: Larger dispersion than the predictions for concrete observables… WHY ?
- Because of « extra ingredients », chosen differently in each model (partly) !!!
- More complex then for the case of jets (several FP coefficients)

New Observables are coming

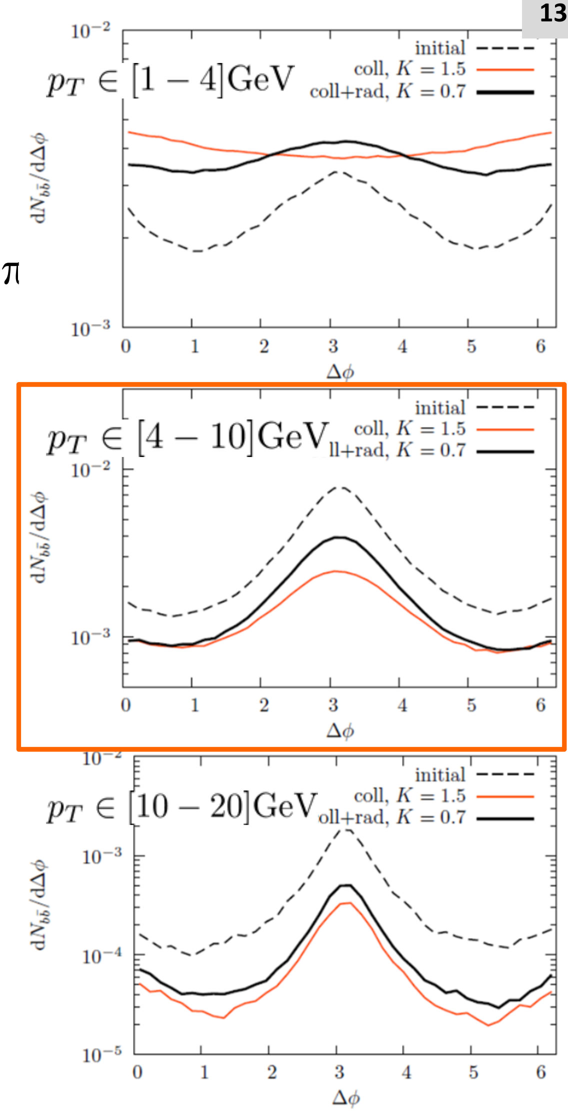
Short term, mid-term, long term,…

What	Good for ?	Caviat
Event shape engineering	Strength and T dependence of the interaction	Might be sensitive to the bulk and initial stage => play collective
Heavy light - correlations	b/c-jet substruture, nature of the interaction	Might be sensitive to various HF creation in pp, to be calibrated
Λ_c, D_s, B_s,…	Understanding hadronization esp. Recombination (if generic enough not to require 1 new free parameter per state) or limits of statistical models	Dynamical treatment of confinement ? Inputs from lQCD probably needed
$v_1(y)$	Constrain (E,B), vorticity, initial tilt of matter initial distribution of HQ in transverse plane	Isn't it a bitt too much for this poor observable ?
Correlations and momentum imbalance		

New observable: azimuthal correlations

M Nahrgang et al, PRC90 (2014), 1305.3823

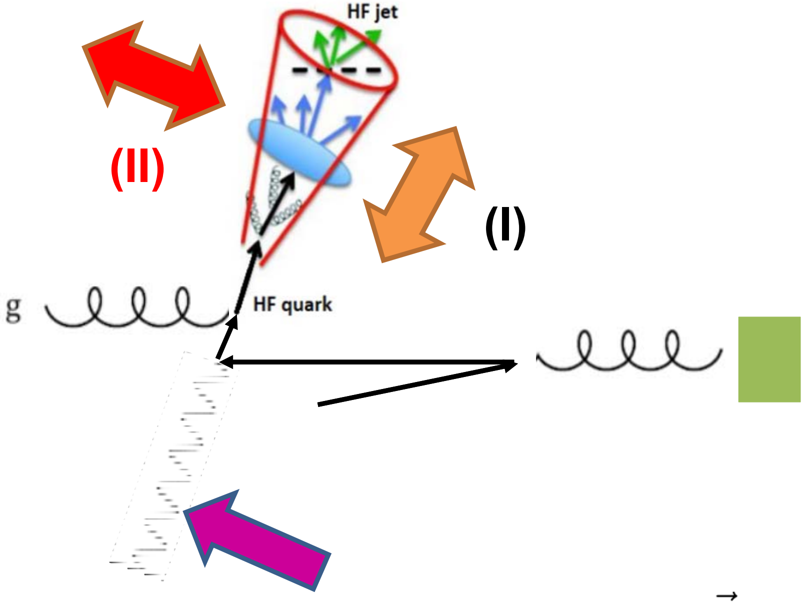
- **NLO effect** simulated with MC@NLO + HERWIG (parton shower)
- Gluon splitting processes lead to an initial enhancement of the correlations around $\Delta\phi=0$; Strong broadening of the $\Delta\phi=\pi$ peak ("vacuum" radiation is dominant)
- For intermediate p_T : increase of the variances due to Eloss from 0.43 (initial NLO) to 0.51 (+20%) for the purely elastic mechanisms and to 0.47 (+10%) for the interaction including **radiative** corrections.
- Correlations at large p_T seem to be dominated by the initial correlations. Nothing will be learned on the Eloss mechanisms in this region
- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production
- Confirmation by other groups (Duke, CCNU-LBL,…)



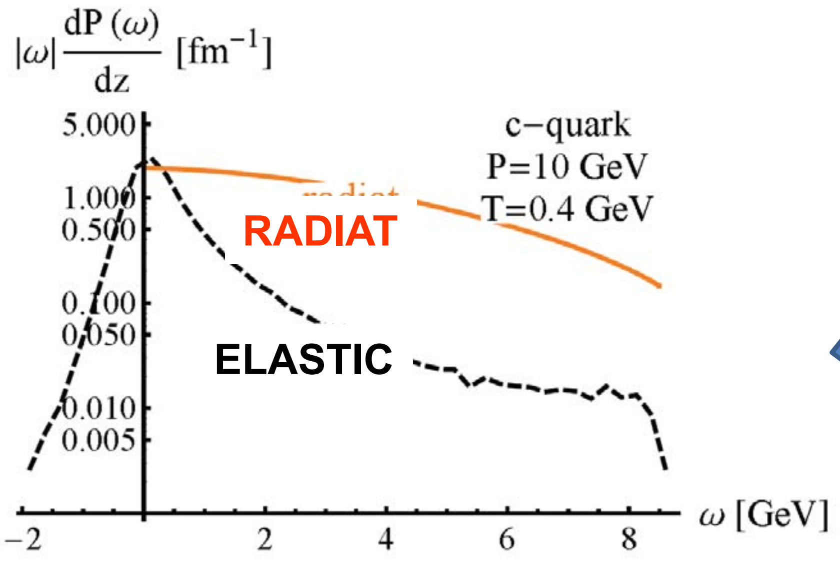
New observable: momentum imbalance

- γ – D/B/c jet /b jet:

In QGP: **Longitudinal fluctuations** of the HQ energy loss crucially depend on the precise mechanism and cannot be measured easily in usual observables like R_{AA} or v_2



No E loss => perfect probe of initial $\vec{P}_{HQ}$

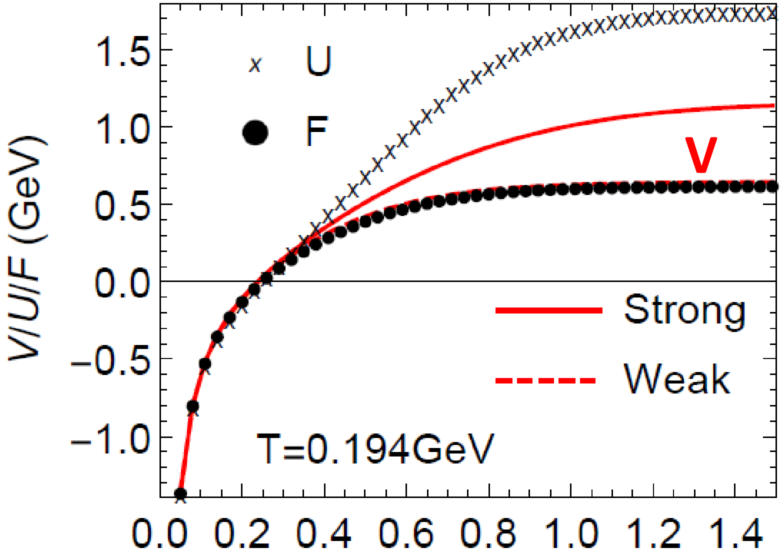


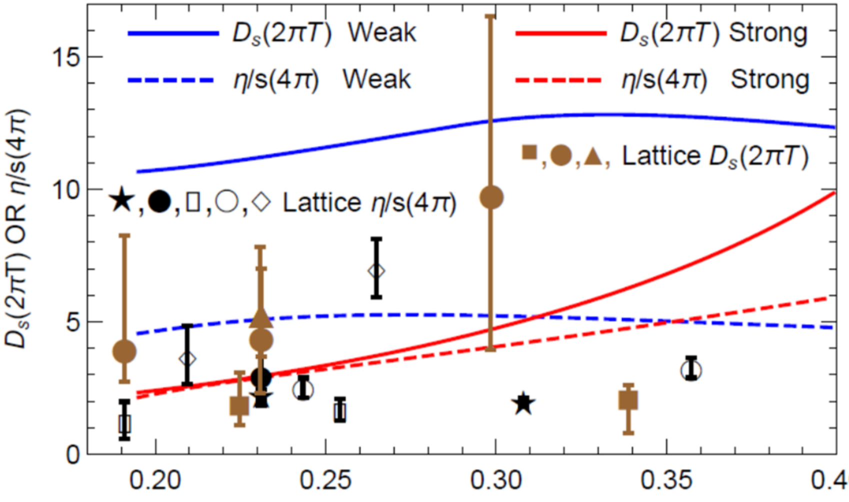
differential probability to loose energy ω per unit time

- Of course: NLO effect in the production mechanisms makes it not so trivial => **Need collaborations between theorists to reach the desirable precision**.
- Challenging measurement => Run4 ?

Recent progresses and future directions

- **Deeper rooting with theory** : TAMU strategy: **S. Y.F. Liu and R. Rapp, PRC97 (2018) 034918**
  - Hamiltonian formulation of a non relativistic effective theory based on a 2-body potential
  - Included in the Luttinger-Ward-Baym formalism -> description of the **equation of state** (EoS)
  - EOS is not enough => evaluation of the **free energy** (./. introduction of Q-Qbar pair) + **quarkonium correlators** ...
  - Allows to self-consistently derive 2 optimal solutions for the potential by calibration on the equivalent lQCD quantities (one « weak » close to the free energy and one « strong » with remnants of the long range forces… non spectral light quarks and spectral densities

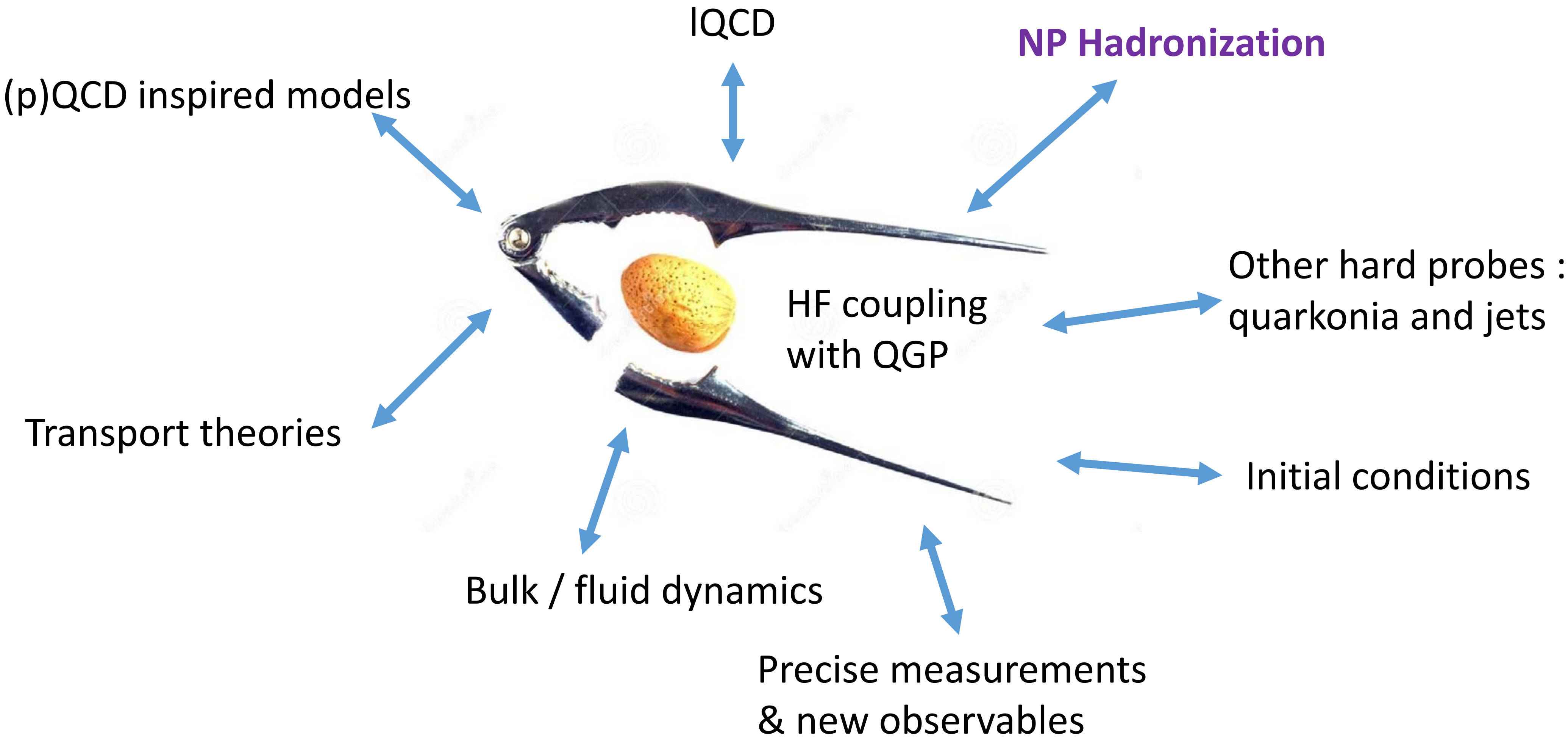




S. Y.F. Liu and R. Rapp Eur. Phys. J. A 56, 44 (2020)

Further comparison with diffusion coefficient favors the « strong » potential

Visual summary



lQCD

NP Hadronization

(p)QCD inspired models

HF coupling
with QGP

Other hard probes :
quarkonia and jets

Transport theories

Initial conditions

Bulk / fluid dynamics

Precise measurements
& new observables

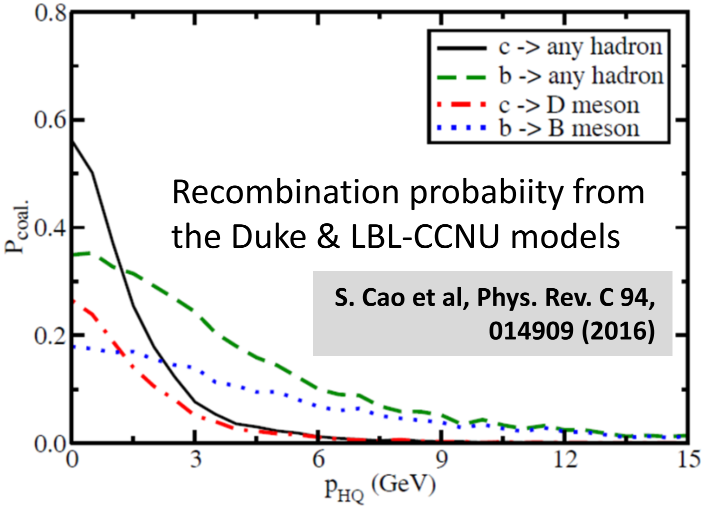
HQ - Hadronization

Acknowledged:

- towards the end of QGP, hadronization of (of equilibrium) HQ can proceed through a dual mechanism:

Low p_T :

- The quark partner(s) are already present in the hot cooling medium
- New specific recombination mechanism; no obvious calibration
- The footprint of reconfinment (?!)
- Crucial to explain the flow bump in $R_{AA}(D)$ and sizable $v_2(D)$ => large impact.



Recombination probabiity from the Duke & LBL-CCNU models

S. Cao et al, Phys. Rev. C 94, 014909 (2016)

High p_T :

- The quark partner(s) needed to create the HF-hadron have to be generated from the vacuum
- « usual » fragmentation calibrated on p+p and e^++e^- data (Petersen,…)

But also energy density dependent (PHSD) !!!

Uncertain (and not disputed enough):

- Genuine physical recombination process:
  - Instantaneous Parton Coalescence with local (x,p) correlations (Greco, Ko & Levai 2003), Xor in momentum space (Oh et al 2009): known violation of energy-momentum conservation, advocated to have small effects at finite p_T
  - Resonance Recombination Model (Ravagli and Rapp, 2009): kinetic c+qbar -> D; spirit of dynamical recombination around T_c ($P_{recomb} = \Delta\tau \times \Gamma_{res}(p)$; a way to solve the energy-momentum conservation issue
  - In medium Fragmentation (Beraudo et al., 2015) : string from HQ + thermal light
- Differences in the « technical implementations » , e.g. normalisation

Collective investigation : Consequences from various **Hadronization Mechanisms**

We define and display the H_{AA} quantity

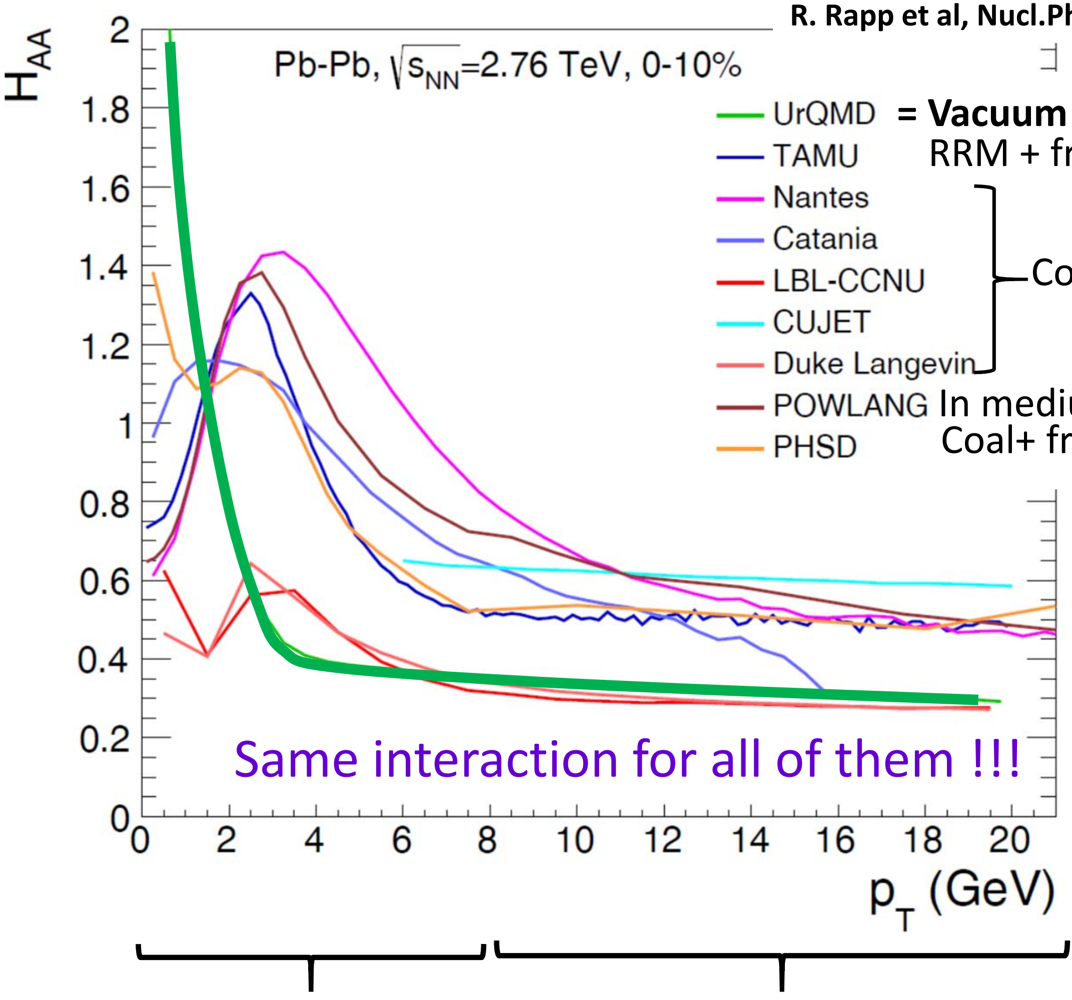
$$H_{AA} = \frac{\frac{dN_D}{dp_T}}{\frac{dN_{c\ \mathrm{final}}}{dp_T}}$$

…which exhibits at best the specific effects of hadronization :

Significant uncertainties !

=> Yes, one can for sure put more constrains with D_s and Λ_c, but probably one has also to converge on more robust schemes for « basic » D mesons

R. Rapp et al, Nucl.Phys.A 979 (2018) 21-86



= **Vacuum = Fragmentation**

RRM + frag

Coal + frag

In medium frag

Coal+ frag

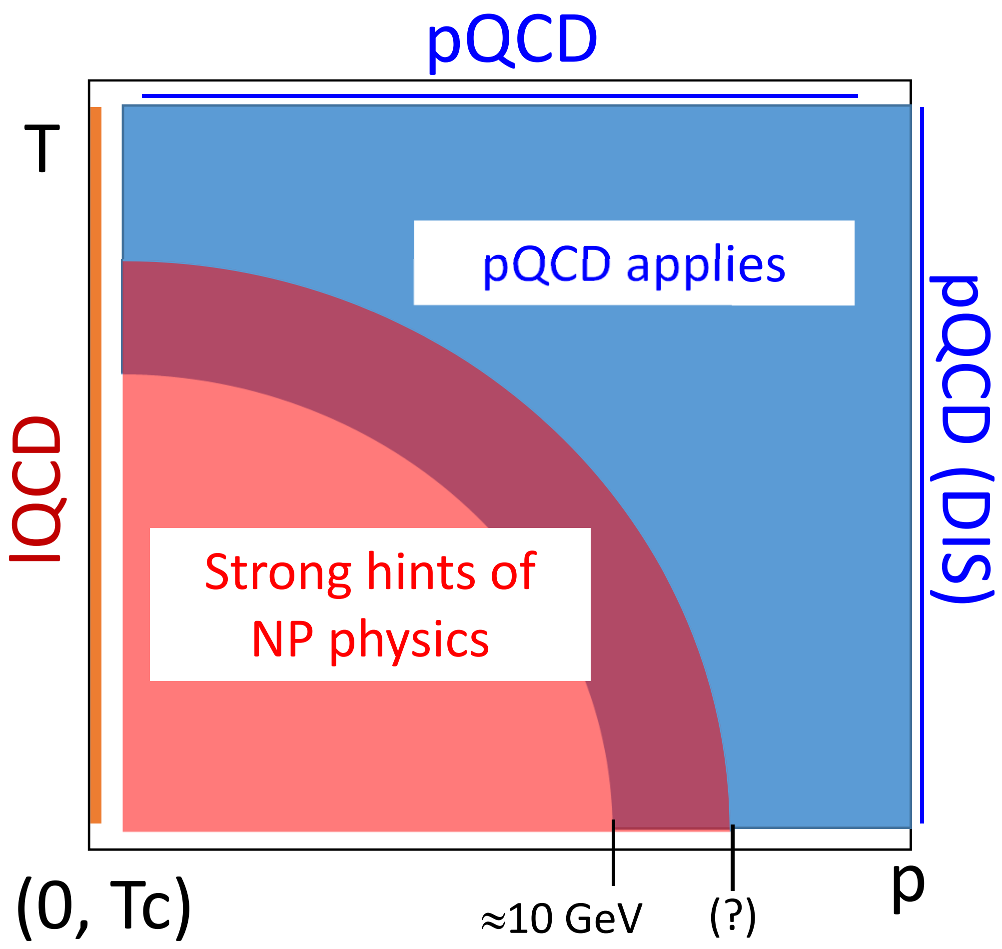
Same interaction for all of them !!!

Recombination

Fragmentation

Conclusions

HF in QGP



- Existing models offer the possibility to describe most of the OHF experimental AA data while being compatible with existing theory constrains…
- … however with unequal precision and no consensus on the physical NP content
- Improvements and quantitative understanding is on their way, but it will still take some time and a lot of efforts => need for ressources, bright (young) people and collective work.
- Open Heavy Flavors are maybe not an ideal probe of QGP yet, but they are quite fascinating and offer bright future for the field, with multiple interconnections (see next slide).